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13. ABSTRACT (Maximum 200 words)

The effects of externally applied uniaxial stresses on III-V double barrier resonant tunneling devices was studied experimentally and theoretically. Devices were fabricated on (001)- and (111)- oriented substrates and subjected to stresses in the plane and perpendicular to the plane of the wafer. The current vs. voltage characteristics of these devices were calculated in the framework of a model that takes into account stress effects on the bandstructure as well as piezoelectric effects. Good qualitative agreement between the experimental and theoretical results was achieved.

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Strain Induced Polarization Effects for III-V Heterostructure Device Applications

Background and Introduction

Many semiconductor heterostructure devices make use of built-in electric fields that are oriented parallel to the direction of crystal growth. The built-in electric fields required for their operation are usually caused by suitably doped layers that have been incorporated during the epitaxial growth process. The depleted parts of these doped layers provide space charge that gives rise to electric fields. Once the structure has been grown, the built-in fields cannot be changed.

An alternative approach to fabricating heterostructures with built-in electric fields is to make use of piezoelectric effects. It has been shown that certain III-V semiconductor heterostructures have strain-induced polarization divergences at the hetero-interfaces. This occurs for pseudomorphic structures grown on (111)-oriented substrates but also for lattice matched structures grown on (001)-oriented substrates if stress along either the (110) or the (1-10) crystal axes is applied. These polarization charges can give rise to large electric fields without the presence of randomly distributed ionized impurities.

Semiconductors with zincblende crystal structure are piezoelectric materials. Off-diagonal strain components induce an electric polarization given by

$$P_i = e_{14}\varepsilon_{jk}$$

where P_i is the induced polarization component, e_{14} is the only non-vanishing piezoelectric constant, and ε_{jk} is the symmetrized strain tensor element. In 1985 it was pointed out that in coherently strained and suitably oriented III-V heterostructures macroscopic polarization fields will appear due to the piezoelectric effect. The crystal symmetry of these materials is such that the polarization is parallel to the growth direction if the epitaxial structure is grown in the (111)-orientation. In that case polarization charges appear at the interfaces between layers that are strained and layers that are unstrained or between layers that are under biaxial compressive and those that are under biaxial dilatant stress. These polarization charges can produce strong electric fields parallel to the growth direction. For other crystal orientations, different polarization directions or no polarization at all, are expected. The symmetry of the piezoelectric tensor leads to vanishing polarization in longitudinally strained III-V heterostructures grown in the (001) direction. However, even structures grown on (001)-oriented substrates will exhibit these interfacial polarization charges if strain along either the (110) or (1-10) crystal axes is applied.

Statement of the Problem Studied

Under this program we showed that piezoelectric effects can give rise to internal electric fields that modulate the conventional current voltage characteristics of lattice matched and pseudomorphic double barrier resonant tunneling devices. For the case of (001)-oriented structures this effect arises under application of stress in the plane of the wafer. For (111)-oriented structures it occurs both with in-plane and with perpendicular-to-plane stress.

Key Results Obtained

We measured current voltage characteristics of AlAs/GaAs/AlAs double barrier structures as a function of external stress. The structures were grown by gas source MBE on (001)-oriented GaAs substrates. Nominal barrier and well thicknesses were 5.0nm and

5.7nm, respectively. The resonant tunneling devices consisted of circular, 100 - 400μm diameter, mesas on rectangular, cleaved pieces of substrate. Uniaxial stress was applied parallel to the (001), the (110), and the (1-10) directions. At 77K, under (001)-stress, the resonance peaks in the current vs. voltage curve shift to larger absolute voltages for both positive and negative applied voltage. In contrast, under (110)-stress, the resonance peaks for both positive and negative bias shift to more positive voltages. For (1-10)-stress we observe a similar shift of the resonances but with opposite sign. Figures 1 and 2 show the experimental data obtained from an AlAs/GaAs structure.
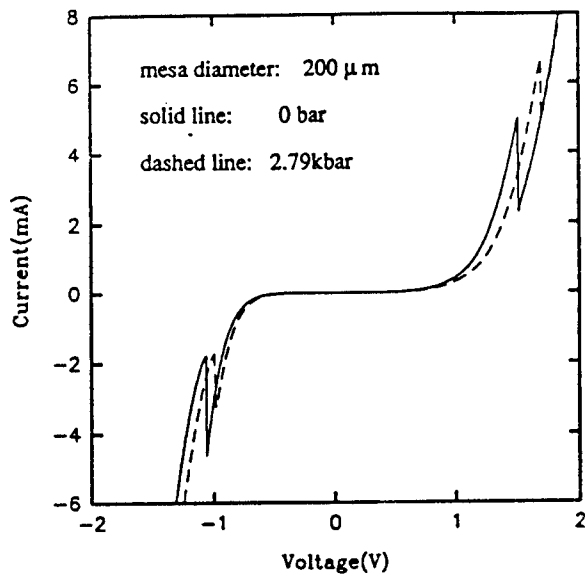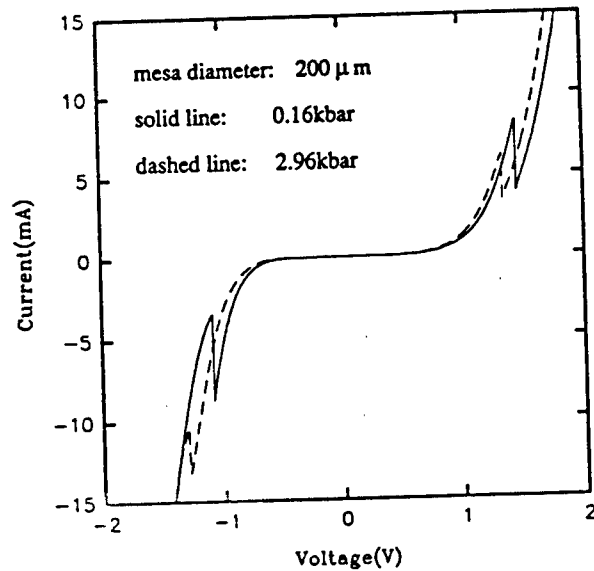

Fig. 1: (001)-oriented structure, (110)-stress.   Fig. 2: (001) structure, (1-10)-stress.

In order to understand the experimental results we calculated the current voltage characteristics of resonant tunneling structures under uniaxial stress. The stress effects on the band alignment were included in the framework of the model solid theory of van de Walle. The symmetric shift of the resonance peaks towards larger absolute voltages under (001)-stress can be attributed to energy band structure changes due to a volume change. We also included in our model the effects associated with the piezoelectric nature of the constituent materials. As expected, stresses along the (110) and (1-10) directions give rise to polarization charges of opposite sign at the AlAs/GaAs interfaces, due to the difference in the piezoelectric constants of the two materials. The polarization charges at the emitter and at the collector interfaces are partially compensated by accumulation and depletion charges, respectively. This implies that even for zero applied voltage the structures have non-symmetric band profiles under stress applied along (110) or (1-10). Consequently, the calculated current voltage characteristics are non-symmetric, in good agreement with our experimental results. Figures 3 and 4 show calculated band profiles and current voltage characteristics for an AlGaAs/GaAs resonant tunneling structure with layer thicknesses equal to those of the experimentally explored structure.
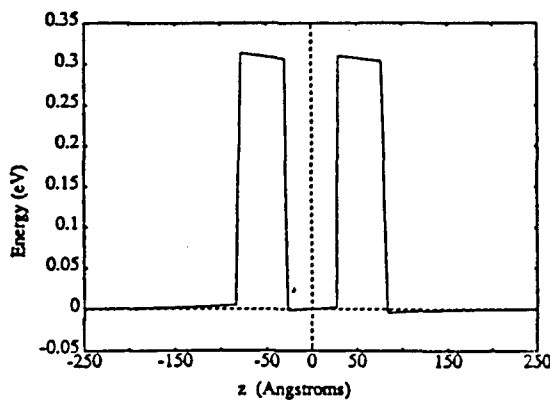
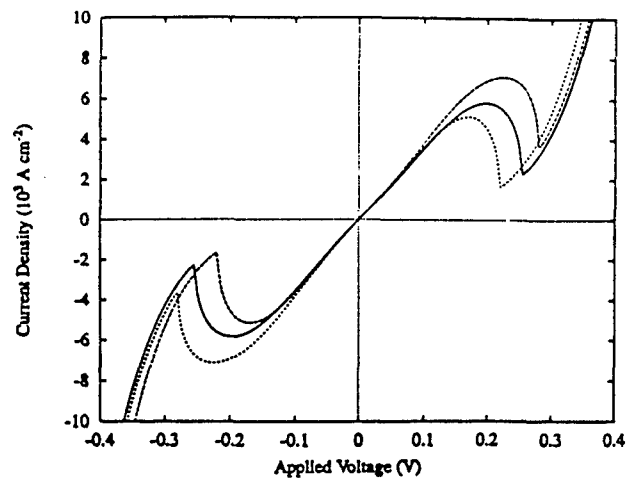Fig.3: Calculated bandprofile, (001)-structure, (1-10)-stress.

Fig.4: Calculated 300K I-V curve, (001)-structure, (110)-stress dashed, (1-10)-stress dotted.

Good progress was made in the difficult area of growth of resonant tunneling structures on (111)-oriented substrates. This success led to further experimental investigation of the piezoelectric effects affecting that type of system. Examples of experimental and theoretical current vs. voltage curves without stress and under (111)-stress are shown in Figures 5 and 6.

mesa diameter: 400 μm
solid line: 0.81kbar
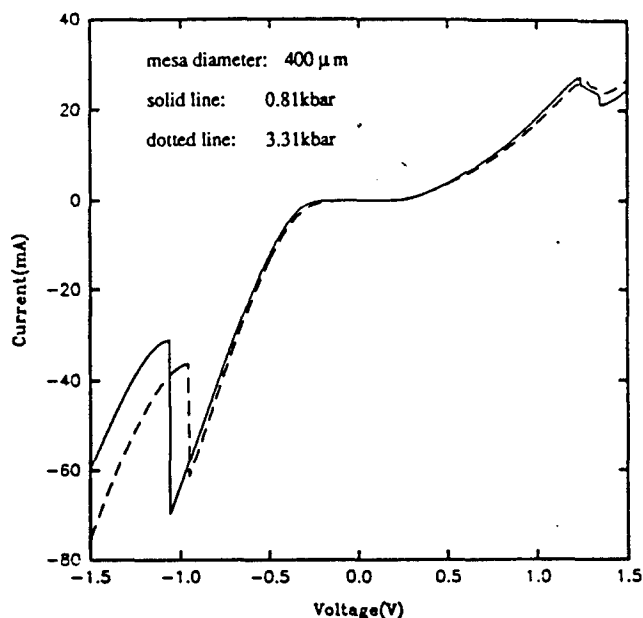dotted line: 3.31kbar
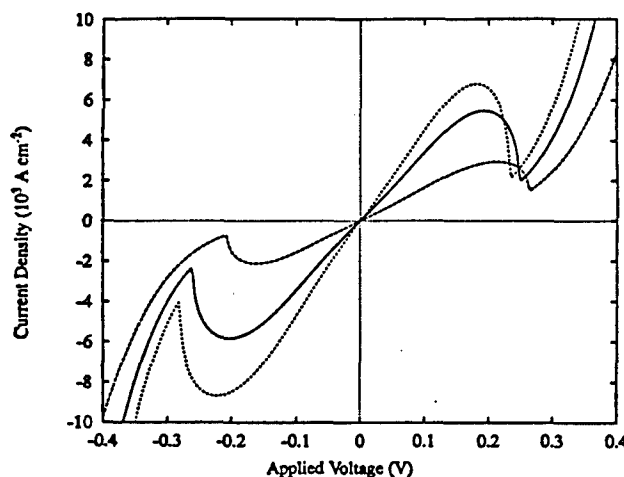
Fig.5: (111)-structure, (111)-stress.   Fig.6: Calculated result (111)-structure.

All results on the resonant tunneling devices were documented in a series of publications in technical journals as listed below.

Additional significant work that was partially supported by this contract dealt with the acousto-optic modulation of III-V semiconductor multiple quantum wells. We analyzed the modulation of the complex linear optical response function by surface acoustic waves on a (001)- and (111)-oriented pseudomorphic multiple quantum well structures. Our results indicated that these structures have considerable potential as acousto-optic modulators. The results were documented in an archival journal article (see list below).

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Presentations

- "The uniaxial stress dependence of the electrical characteristics of of nGaAs/AlGaAs/nGaAs single barrier heterostructures", L.Cong, T.J. Miller, F. Williamson, M.I. Nathan, and P.P. Ruden, APS March Meeting 1993.
- "Piezoelectric effects in double barrier resonant tunneling structures", J.D. Albrecht, L.Cong, M.I. Nathan, P.P. Ruden, and D.L. Smith, APS March Meeting 1995.
- "Stress effects on resonant tunneling characteristics", J.D. Albrecht, L.Cong, P.P. Ruden, M.I. Nathan, and D.L. Smith, APS March Meeting 1996.

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